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TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 329

SOME EFFECTS OF AIR FLOW ON THE PENETRATION AND DISTRIBUTION OF OIL SPRAYS

By A. M. Rothrock and E. G. Beardsley
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Summary

Tests were made at the Langley Memorial Aeronautical Laboraotry, Langley Field, Virginia, to determine the effects of air flow on the characteristics of oil sprays from fuel injection valves. The work was done with the N.A.C.A. Spray Photography Equipment, the spray chamber of which was altered to simulate an oil engine combustion chamber of the vertical disk type. Air under pressure was admitted to the spray chamber at a rate which gave a static pressure of 200 lb. per sq.in. and a maximum velocity in the chamber of 59 ft. per sec. The air was discharged through holes either at the sides of the chamber or at the end of the chamber. The fuel oil was injected at 6000 lb. per sq.in. pressure. Four nozzles were tested, one containing seven orifices and three containing single orifices with diameters of 0.006, 0.012, and 0.022 in., respectively.

Curves and photographs are presented showing the air flow throughout the chamber and the effects of the air flow on the fuel spray characteristics. It was found that the moving air had little effect on the spray penetration except with the 0.006

in. orifice. The moving air did, however, affect the oil particles on the outside of the spray cone. After spray cut-off, the air flow rapidly distributed the atomized fuel throughout the spray chamber.

Introduction

With the advent of the high-speed compression-ignition engine the problem of mixing the fuel and the air in the combustion chamber has become one of increasing importance due to the short time available for the mixing. This mixing of the fuel and air can be done either by designing the fuel injection nozzle so that the spray is distributed to all parts of the combustion chamber, or by designing the combustion chamber or air induction passage so that sufficient turbulence is created to insure that all the air moves through the fuel spray. In most cases, a combination of the two methods is used.

Experiments have been conducted to determine the advantage of air flow created by directing the air in the intake manifold or around the intake valves. Kemper (Reference 1) found that by directing the inlet air flow of a compression-ignition engine the i.m.e.p. was raised from 82 to 96 lb. per sq.in., and the fuel consumption was decreased from 0.60 to 0.51 lb. per i.hp per hr. No changes were made in either the valves or the cylinder head of the engine. Hesselman (Reference 2) found that directing the flow of inlet air by means of shielded intake valves decreased the fuel consumption 30 per cent. Ricardo (Reference 3) found that by inducing rotation of the air in the cylinder of a sleeve valve engine, the performance of the engine, with the fuel sprayed along the side of a cylindrical combustion chamber, did not change materially for a fuel nozzle with a diameter of 0.019 in. and one with a diameter of 0.030 in. (Fig. 1). He states, "In all cases the best results are obtained when the jet is a plain round hole and no attempt whatever is made to pulverize the fuel, the latter being done quite efficiently and adequately by the air swirl within the cylinder."

In other cases the air flow is produced by an orifice between the cylinder and combustion chamber. The flow in engines of this type differs from the former in that the motion of the air is produced by the moving piston and the velocity increases as the piston approaches top center, reaching a maximum approximately 25° before this point. This method is the more prevalent of the two. Numerous examples can be cited; among them are the Worthington, Tartrais-Peugeot, Deutz, and Banner (Fig. 2).

Unfortunately, the exact magnitude of the velocity of the air within the cylinder or combustion chamber of a compression-ignition engine is a very difficult quantity to measure, due to the inaccessibility of the interior of the engine and the rapid sequence of events. Consequently, most of the data published have not been on the effects of the air flow on the fuel spray, but on the variation in engine performance with different types of cylinders, pistons, combustion chambers, and fuel injection systems.

The staff of the Langley Memorial Aeronautical Laboratory at Langley Field, Virginia, have been conducting an extensive research on the performance of the N.A.C.A. Universal Test engine (Reference 4) operated as a compression-ignition engine with a vertical disk-type combustion chamber (Fig. 3). With this cylinder head the mixing of the fuel and air is obtained by injecting the fuel through a multi-orifice nozzle and by restricting the passage between the combustion chamber and the cylinder so that air flow is produced in the chamber. Both the size and distribution of the orifices in the fuel nozzle and the size of the orifice between the combustion chamber and cylinder have been varied.

During these tests it was found desirable to determine the effect of air flow on the fuel spray. This was accomplished by means of the N.A.C.A. Spray Photography Equipment (Reference 5). The spray chamber of this apparatus was altered to simulate the vertical disk-type combustion chamber used on the Universal Test Engine. Fuel was injected through single-orifice and multi-orifice nozzles under an injection pressure of 6000 lb. per sq.in. into moving air at room temperature and a pressure of 200 lb. per sq.in. This air pressure corresponds to the maximum density of the air in the combustion chamber for a compression ratio of 13.6. The density at the end of the compression stroke, and not the pressure, was used, since it has been shown (Reference 6) that it is the density and not the pressure of the air that affects the spray penetration and distribution.

Before starting these tests, it was desirable to know the maximum air velocity in the combustion chamber. An approximation of the velocity of the air through the orifice between the cylinder and combustion chamber was obtained by assuming that at every instant during the compression stroke of the engine the air density is the same in the combustion chamber as in the cylinder. The total volume of air at any angle θ of the crank is given by the equation:

$$V_\theta = V_c + Ar\,(1 - \cos\theta) + A\,l\,\left(1 - \sqrt{1 - \frac{r^2}{l^2}\sin^2\theta}\right)$$

in which V_θ is the total volume at any angle θ,

A is the piston area,

r is one-half the stroke,

l is the length of the connecting rod

V_c is the volume of the combustion chamber.

The rate of change of volume with respect to θ is:

$$\frac{dV_\theta}{d\theta} = Ar\sin\theta + \frac{A\,l\,\frac{r^2}{l^2}\sin\theta\cos\theta}{\sqrt{1 - \frac{r^2}{l^2}\sin^2\theta}}$$

where $\frac{dV_\theta}{d\theta}$, is in unit volume per radian. The rate of volume inflow to the combustion chamber is:

$$\frac{V_c}{V_\theta} \times \frac{dV_\theta}{d\theta}.$$

The linear velocity v_θ of inflow to the combustion chamber is the volume velocity divided by the area (a) of the orifice between the combustion chamber and the cylinder:

?

$$v_\theta = x \; \frac{V_c}{aV_\theta} \; \frac{dV_\theta}{d\theta} \,.$$

The curve representing the velocity at any instant through the orifice of this combustion chamber for an engine speed of 1500 r.p.m. is shown in Figure 4. From this curve a velocity of 59 ft. per sec. was chosen for studying the effects of air flow on fuel sprays.

Test Apparatus and Procedure

Figure 5 shows the arrangement of the spray chamber altered to simulate the air flow in the engine cylinder head. The air was supplied to the chamber through a throttling valve from a tank containing compressed air at 2000 lb. per sq.in. pressure. A velocity survey of the chamber was made by means of five Pitot tubes (Fig. 6) held in a fitting screwed into the chamber in place of the injection valve and attached to a suitable mercury manometer. They could be set so that their ends were at distances of 1/2, 1-3/8, 2-3/8, or 3-3/8 in. from the injection valve end of the chamber. The velocities of the air were determined with the air being discharged at the sides of the chamber and at the end of the chamber (Fig. 7). The size of the air discharge holes was such that an air velocity in the rectangular orifice of 59 ft. per sec. was recorded when the static pressure was held at 200 lb. per sq.in.

The lines of air flow in the chamber were obtained by placing a white metal plate covered with a mixture of kerosene and lamp black in the center of the chamber parallel to the direction of flow (Figs. 8 and 9). In Figure 8, which shows the air discharging at the sides of the chamber, the dark section was produced by vortices which accumulated the lamp black and kerosene. The return of the air to the outlet holes is seen to take place along the edges of the chamber. From Figure 9 it is seen that with the air discharging at the end of the chamber a dead space was created between the exit holes. A comparison of the two figures shows that the air flow in the engine was more nearly approximated with the air discharging from the sides of the chamber.

To operate the apparatus the flow of air from the compressed air tank was adjusted so that the static pressure in the spray chamber was maintained at 200 lb. per sq.in. The fuel oil was then injected into the spray chamber and high-speed moving pictures of the spray formation and development were taken at the rate of 2000 per second. Three sets of pictures were taken for each nozzle, one in still air, one with the air discharging at the top and bottom of the chamber, and one with the air discharging at the end of the chamber. The duration of injection was approximately 0.004 second.

R e s u l t s

Figure 10 shows the effect of air flow on the fuel spray from a multi-orifice nozzle with the air discharging from the top and bottom of the chamber. The moving air had apparently little effect on the spray until after cut-off. From this point on the finely atomized fuel was distributed throughout the chamber by the air flow.

Single-orifice nozzles show more clearly the effect of air flow on the oil sprays. Figure 11 shows the effect of air flow on the spray from a 0.006-inch diameter nozzle. The finely atomized oil on the edges of the spray was stopped by the moving air and carried back toward the injection nozzle during injection. As in the case of the multi-orifice nozzle, the oil in the center cone was little affected until cut-off, after which the air flow distributed the spray throughout the chamber. The effect on sprays from 0.012 and 0.022-inch orifices (Figs. 12 and 13), is approximately the same as on the spray from the 0.006-inch orifice. The effect of air flow on spray penetration is shown in Figures 14, 15, and 16 for the three single orifices. There is a distinct decrease in penetration under air flow with the 0.006-inch orifice. The decrease in penetration for the 0.012 and 0.022-inch orifices is negligible. It is particularly interesting to note that the air flow has less effect on the spray penetration than on the spray distribution.

The oil particles around the edges of the spray cone are continually opposed by the moving air while those in the center are almost completely surrounded by other oil particles moving in the same direction. After cut-off the whole spray has only its own kinetic energy, which is quickly dissipated against the moving air. The fact that the moving air distributes the fuel spray rapidly throughout the spray chamber after cut-off indicates that the spray core is made up of individual particles of oil and not a solid stream. This point has also been brought out by Kuehn (Reference 7). Unless the center cone of the spray is made up of drops of oil and not a solid core, it is difficult to explain how the air with a density of 1/50 that of the oil is capable of distributing the spray throughout the chamber immediately at the end of injection. The atomization of the center cone of a spray issuing from a single round orifice and the phenomenon of the transformation of the jet from a smooth stream at low pressures to a highly atomized spray at high pressures are clearly shown by observing the discharge from the N.A.C.A. coefficient of discharge apparatus (Reference 8). With this apparatus it is possible to observe discharges lasting several seconds from orifices of the size investigated under pressures up to 8000 lb. per sq.in. A detailed discussion of this phenomenon is given by Kuehn (Reference 7), who also mentions the oil cloud hovering around the discharge nozzle, but makes no mention of the fact that this cloud surrounds the whole jet. This is probably because he was working with atmospheric pressure. Kuehn (Reference 9) has computed the distance traversed by a single drop due to its kinetic energy and has found it to be approximately an inch for the total period of injection. His computations are substantiated by the low penetration of the drops on the edge of the oil spray as shown in the spray photographs.

Conclusions

The results of these tests indicate that at room temperatures the maximum air velocity in a large connecting orifice between a cylinder and a vertical disk-type combustion chamber has little effect on the penetration of sprays from fuel valve nozzles having orifice diameters of 0.012 and 0.022-inch. However, the penetration of a spray from a 0.006-inch diameter orifice is considerably reduced. It may be concluded that the effect of air flow on spray penetration increases as the diameter of the orifice decreases. The principal effect of the air flow during injection is to increase the distribution of the fuel from the outside of the spray cone. After cut-off the air flow distributes all the fuel throughout the spray chamber.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., November 11, 1929.

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9. Kuehn, Dr. R. : Atomization of Liquid Fuels, Part III. N.A.C.A. Technical Memorandum No. 331, 1925.

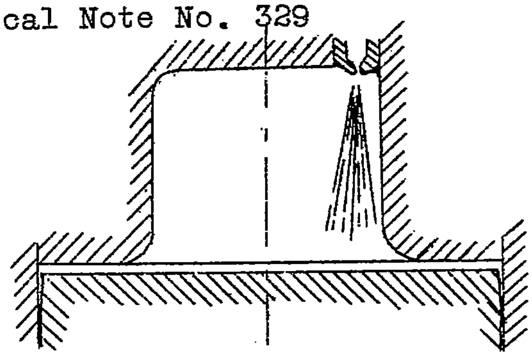
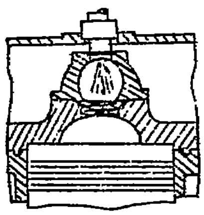
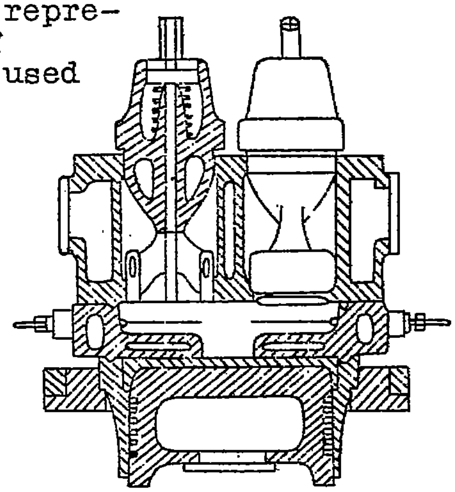


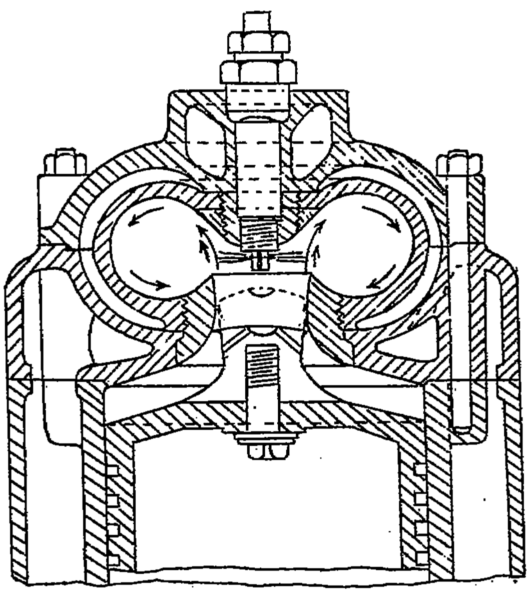
Fig.1 Diagramatic representation of combustion chamber used by Ricardo.



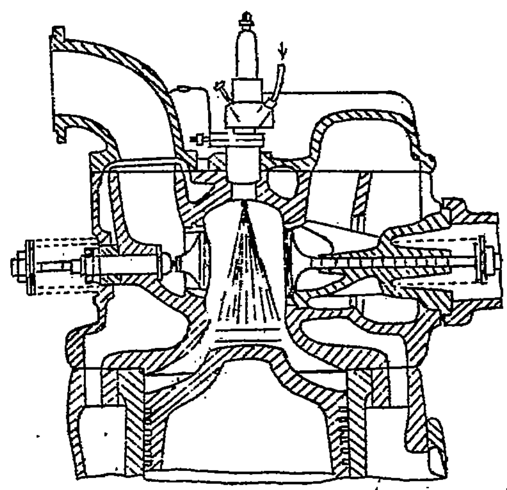
Worthington



Banner



Tartrais-Peugeot



Deutz

Fig.2 Combustion chambers with air flow produced by motion of the piston.

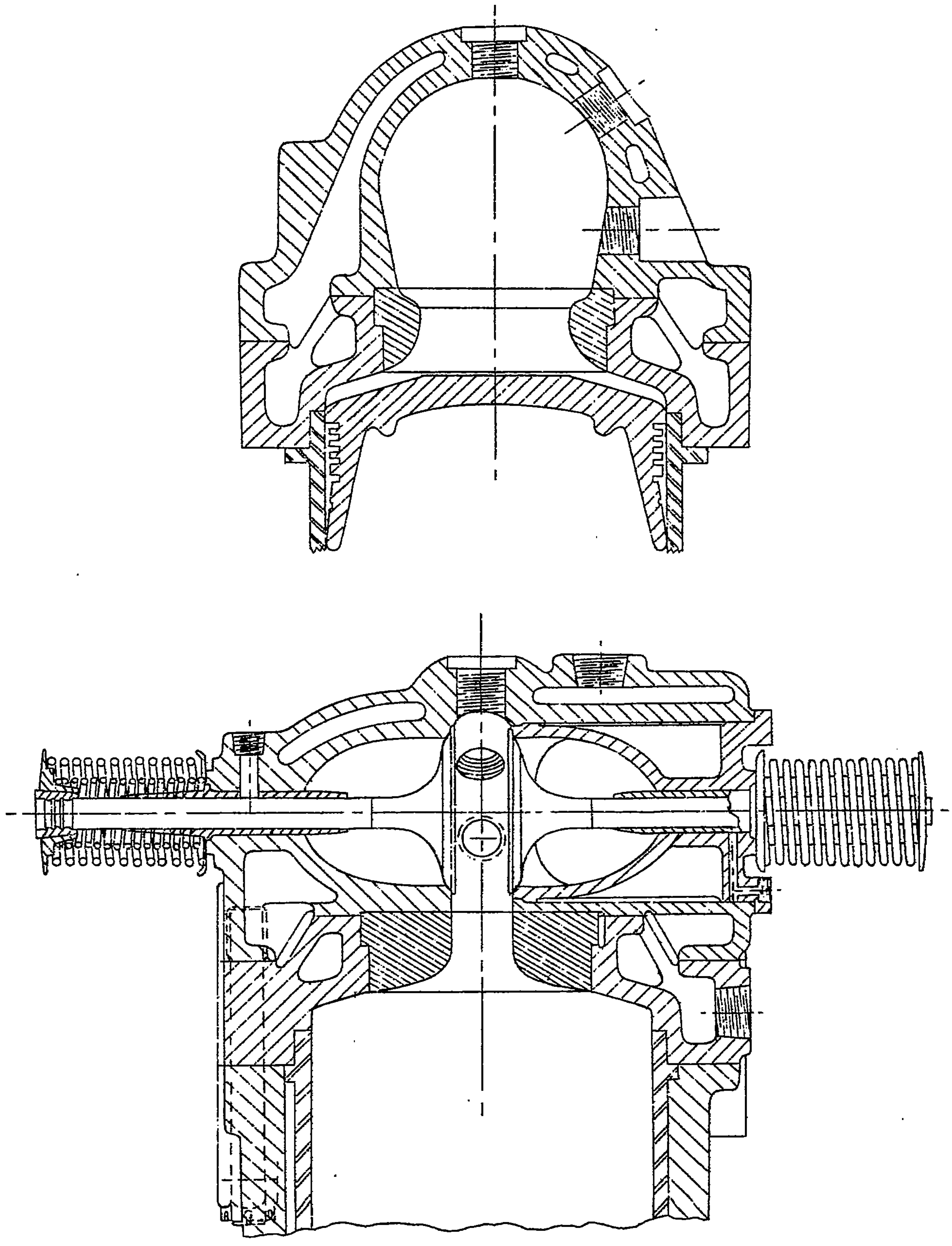
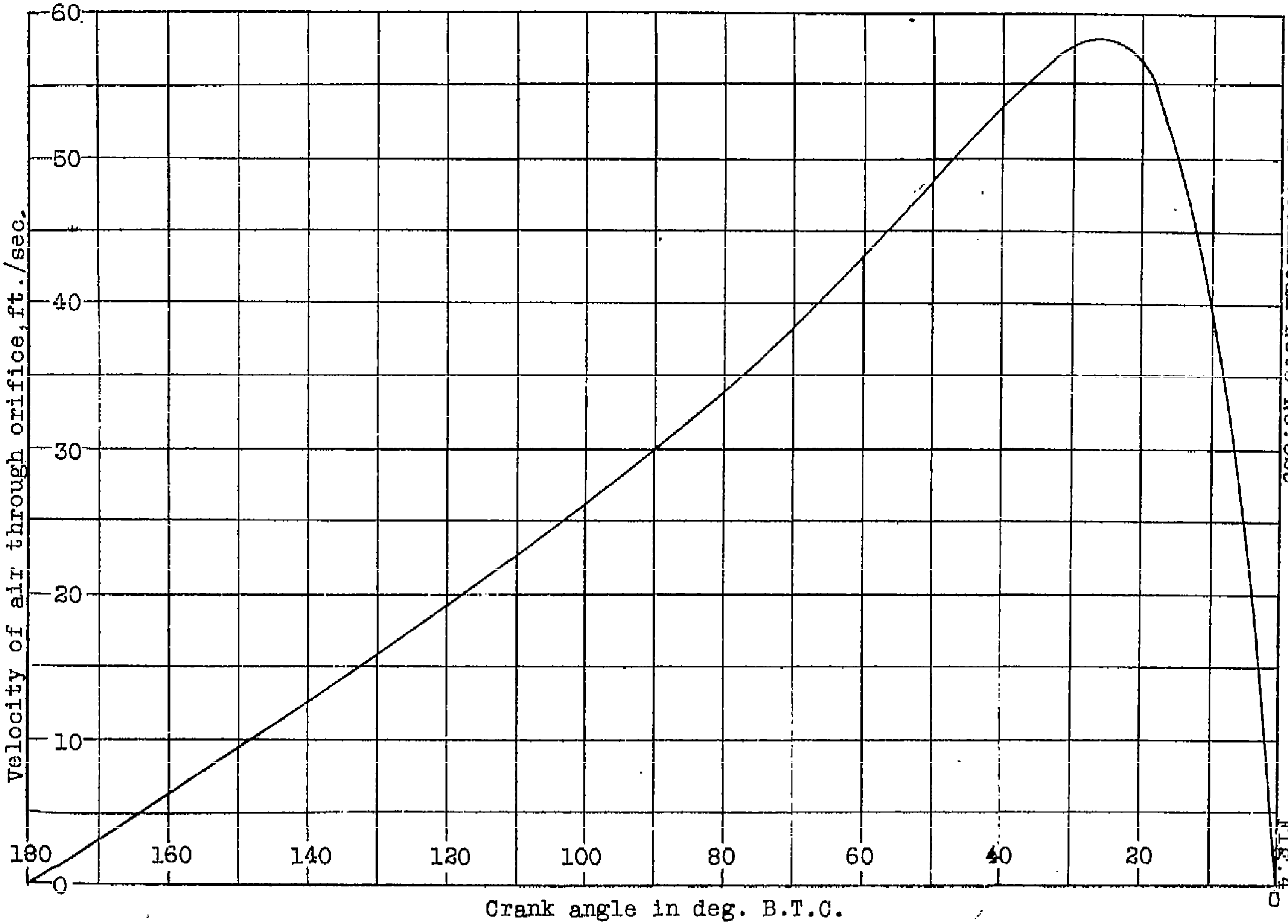


Fig.3 N.A.C.A. vertical disk-type combustion chamber.



Velocity of air through orifice, ft./sec.
60
50
40
30
20
10
0
180
160
140
120
100
80
60
40
20
0
Crank angle in deg. B.T.C.

Fig.4

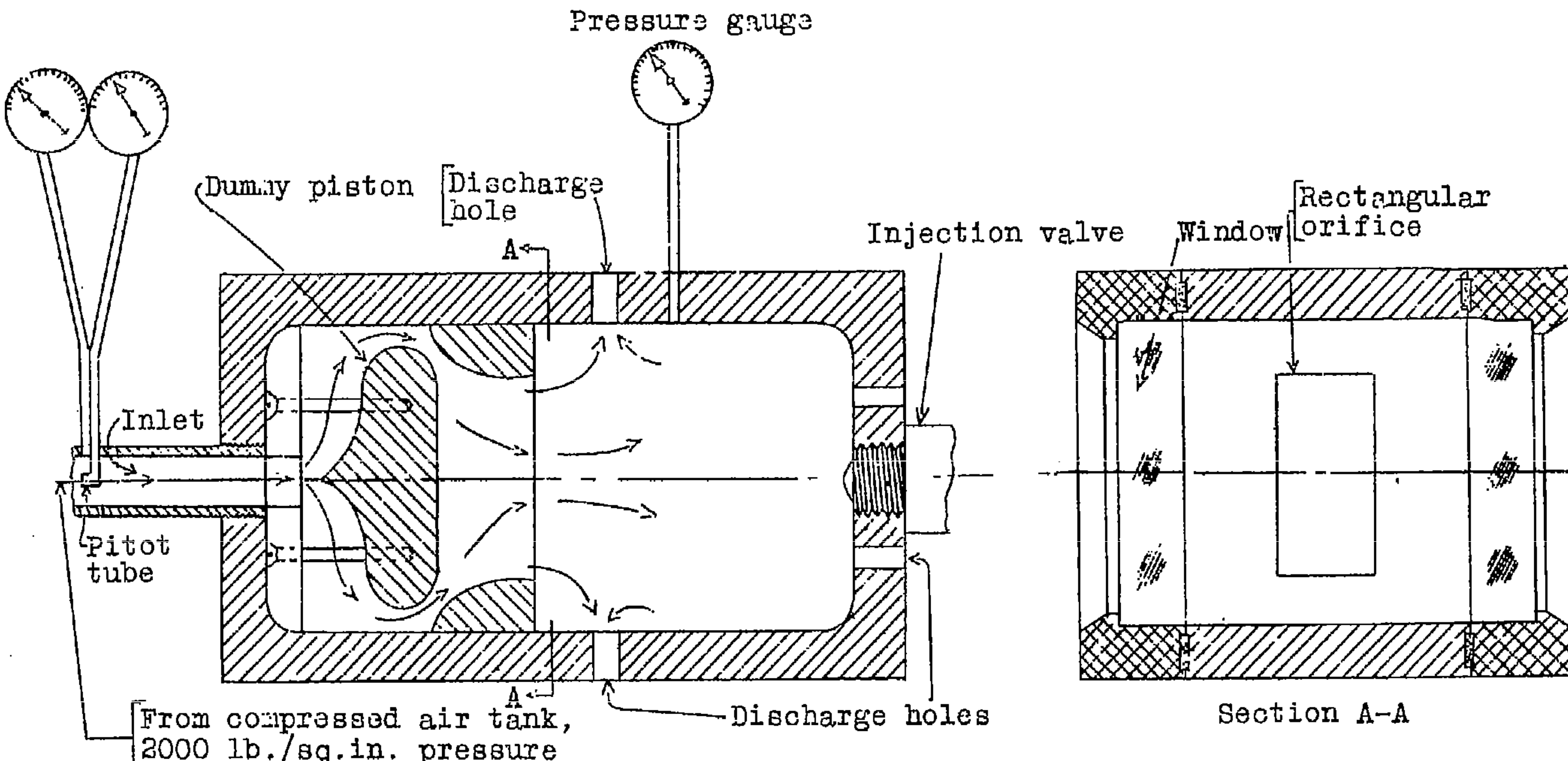


Fig.5 Diagrammatic arrangement of apparatus for studying effect of air flow on fuel sprays.

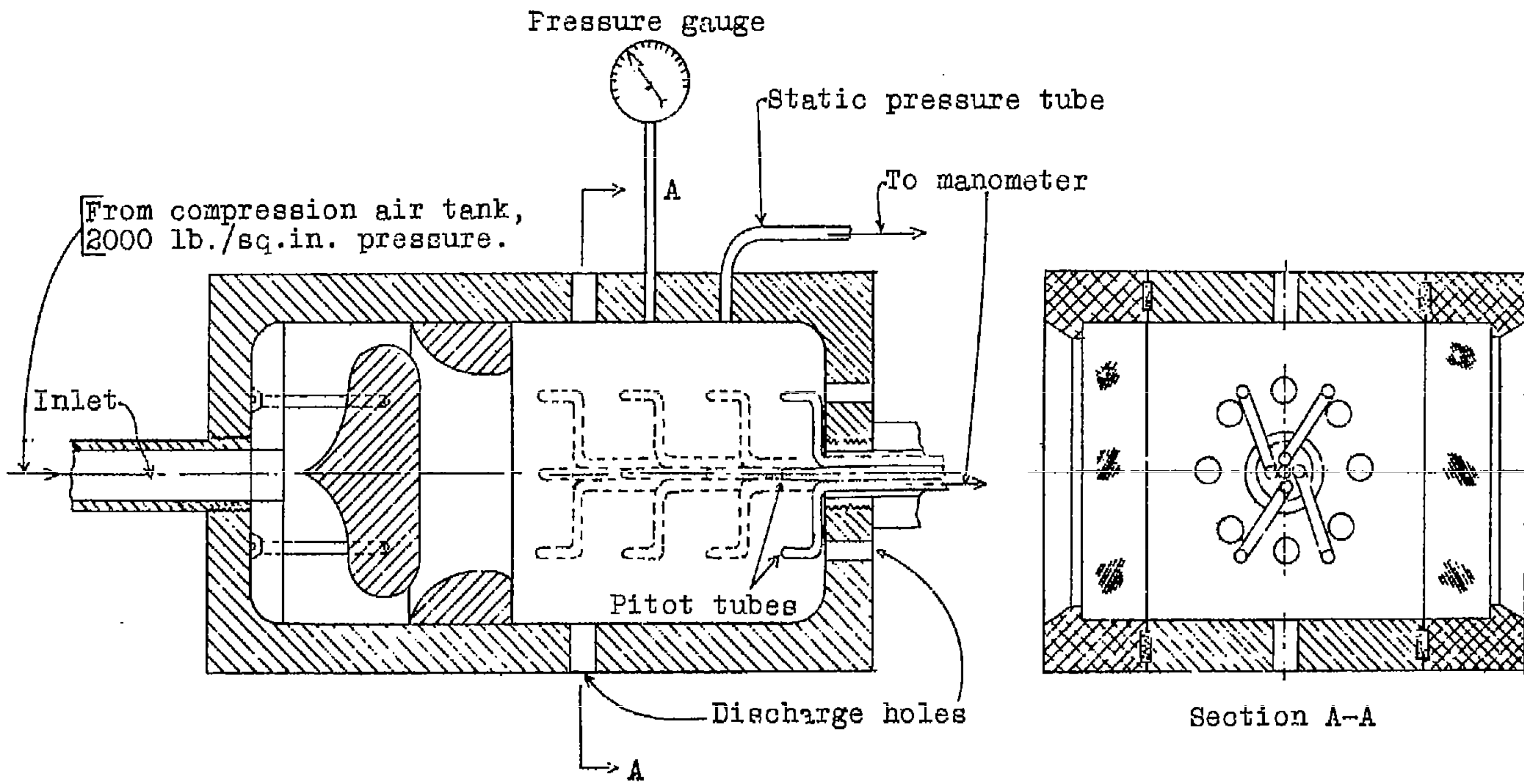


Fig.6 Diagrammatic arrangement of apparatus for making velocity survey of chamber.

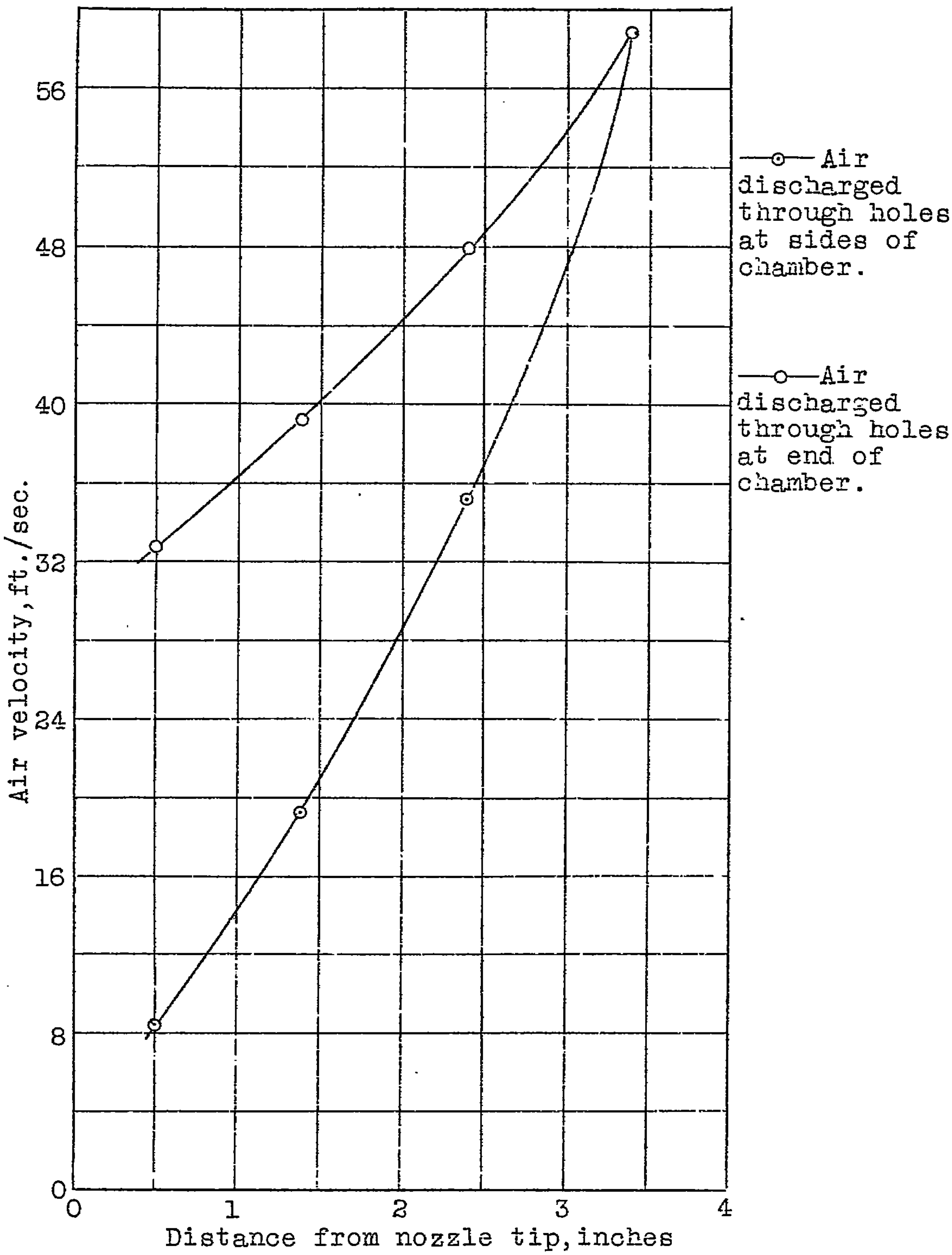


Fig.7 Velocity survey of spray chamber,
Static chamber air pressure, 200 lb./sq.in.

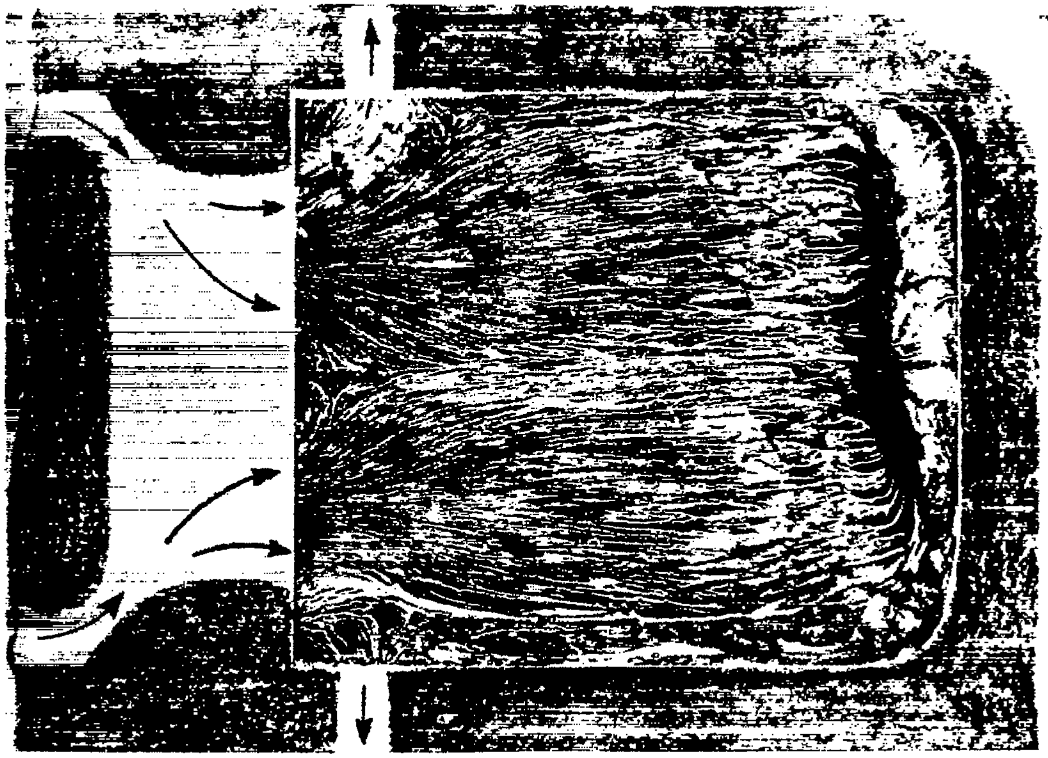


Fig.8 Pattern of air flow in spray chamber.Air discharged through holes at sides of chamber.

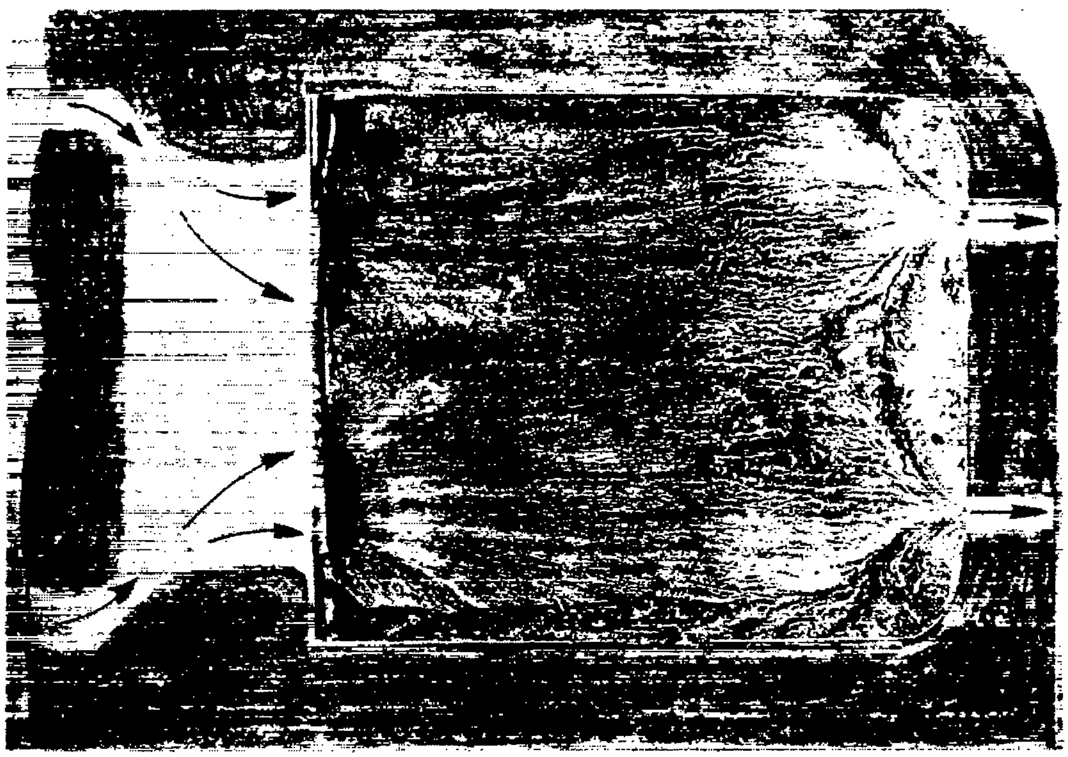
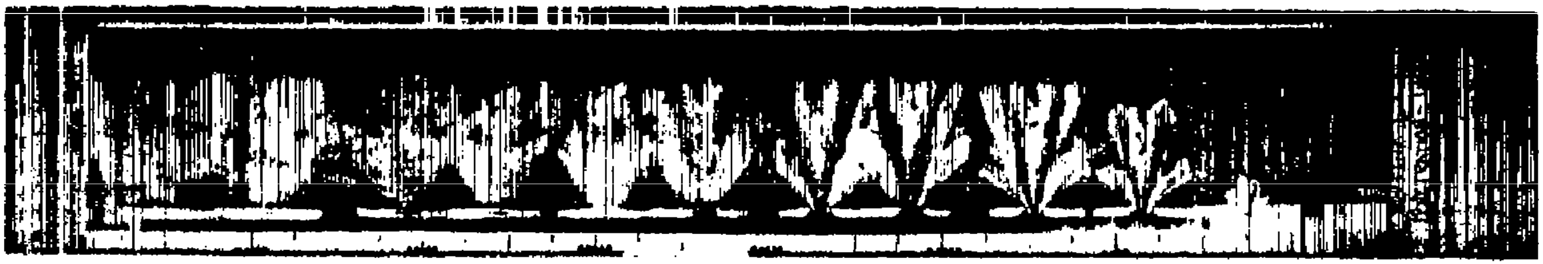


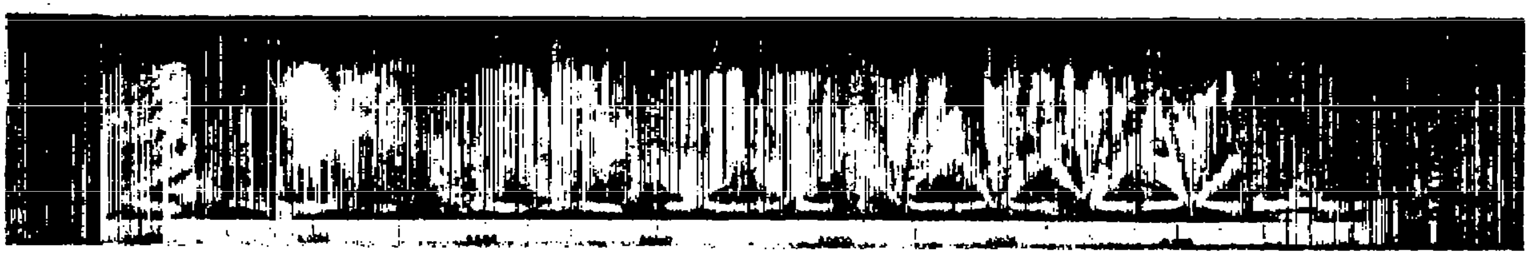
Fig.9 Pattern of air flow in spray chamber.Air discharged through holes at end of chamber.



TIME - SECONDS

INJECTION PRESSURE 6,000 LB. PER SQ.IN. CHAMBER PRESSURE 200 LB. PER SQ.IN.

STILL AIR



TIME - SECONDS

INJECTION PRESSURE 6,000 LB. PER SQ.IN. CHAMBER PRESSURE 200 LB. PER SQ.IN.

INITIAL AIR VELOCITY 60 FT. PER SECOND

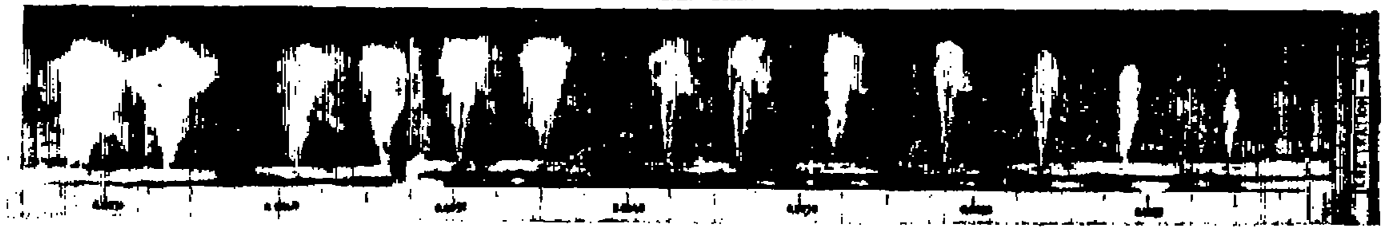
EFFECT OF AIR VELOCITY ON OIL SPRAYS

SEVEN-ORIFICE INJECTION VALVE

Fig.10

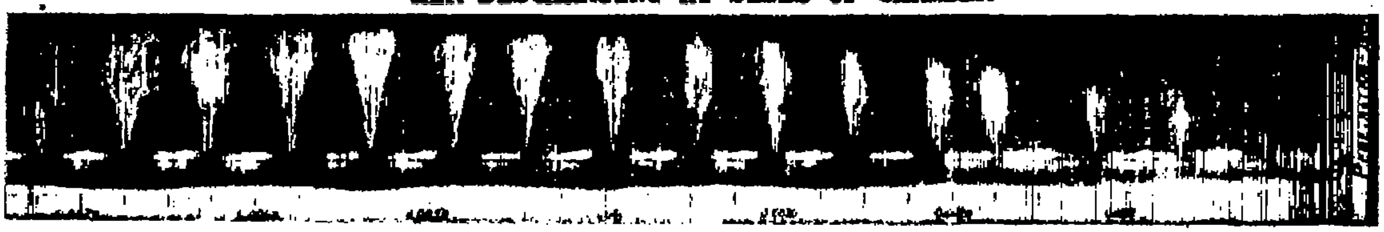
TIME - SECONDS

STILL AIR



TIME - SECONDS

AIR DISCHARGING AT SIDES OF CHAMBER



TIME - SECONDS

AIR DISCHARGING AT END OF CHAMBER

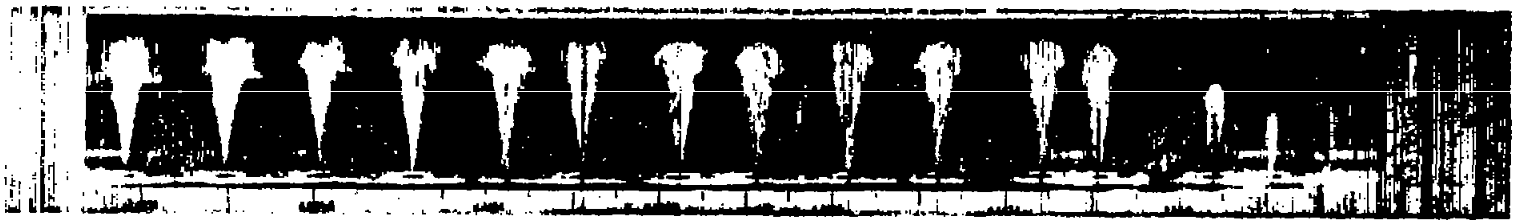
INJECTION PRESSURE 6,000 LB. PER SQ.IN. CHAMBER PRESSURE 200 LB. PER SQ.IN.

INITIAL AIR VELOCITY 60 FT. PER SECOND

EFFECT OF AIR VELOCITY ON OIL SPRAYS

ORIFICE DIAMETER 0.006 INCH

Fig.11


TIME - SECONDS

STILL AIR


TIME - SECONDS

AIR DISCHARGING AT SIDES OF CHAMBER


TIME - SECONDS

AIR DISCHARGING AT END OF CHAMBER

INJECTION PRESSURE 6,000 LB. PER SQ.IN. CHAMBER PRESSURE 200 LB. PER SQ.IN.

INITIAL AIR VELOCITY 60 FT. PER SECOND

EFFECT OF AIR VELOCITY ON OIL SPRAYS

ORIFICE DIAMETER 0.012 INCH

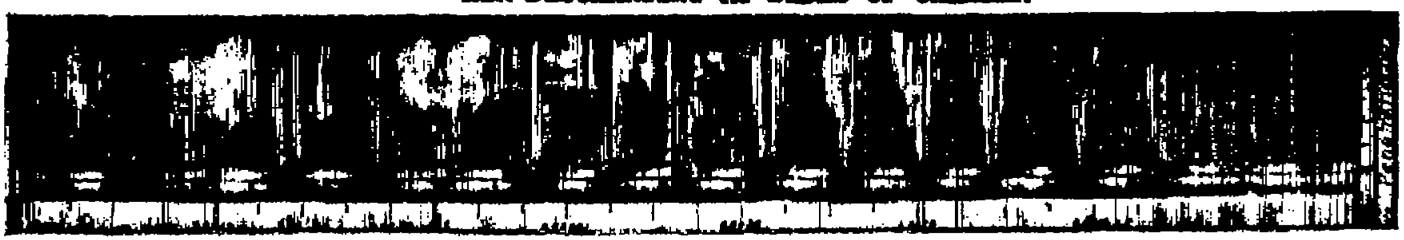
Fig.12

TIME - SECONDS

STILL AIR

TIME - SECONDS

AIR DISCHARGING AT SIDES OF CHAMBER



TIME - SECONDS

INJECTION PRESSURE 6,000 LB. PER SQ.IN. CHAMBER PRESSURE 200 LB. PER SQ.IN.

INITIAL AIR VELOCITY 60 FT. PER SECOND

EFFECT OF AIR VELOCITY ON OIL SPRAYS.
ORIFICE DIAMETER 0.022 INCH.

Fig.13

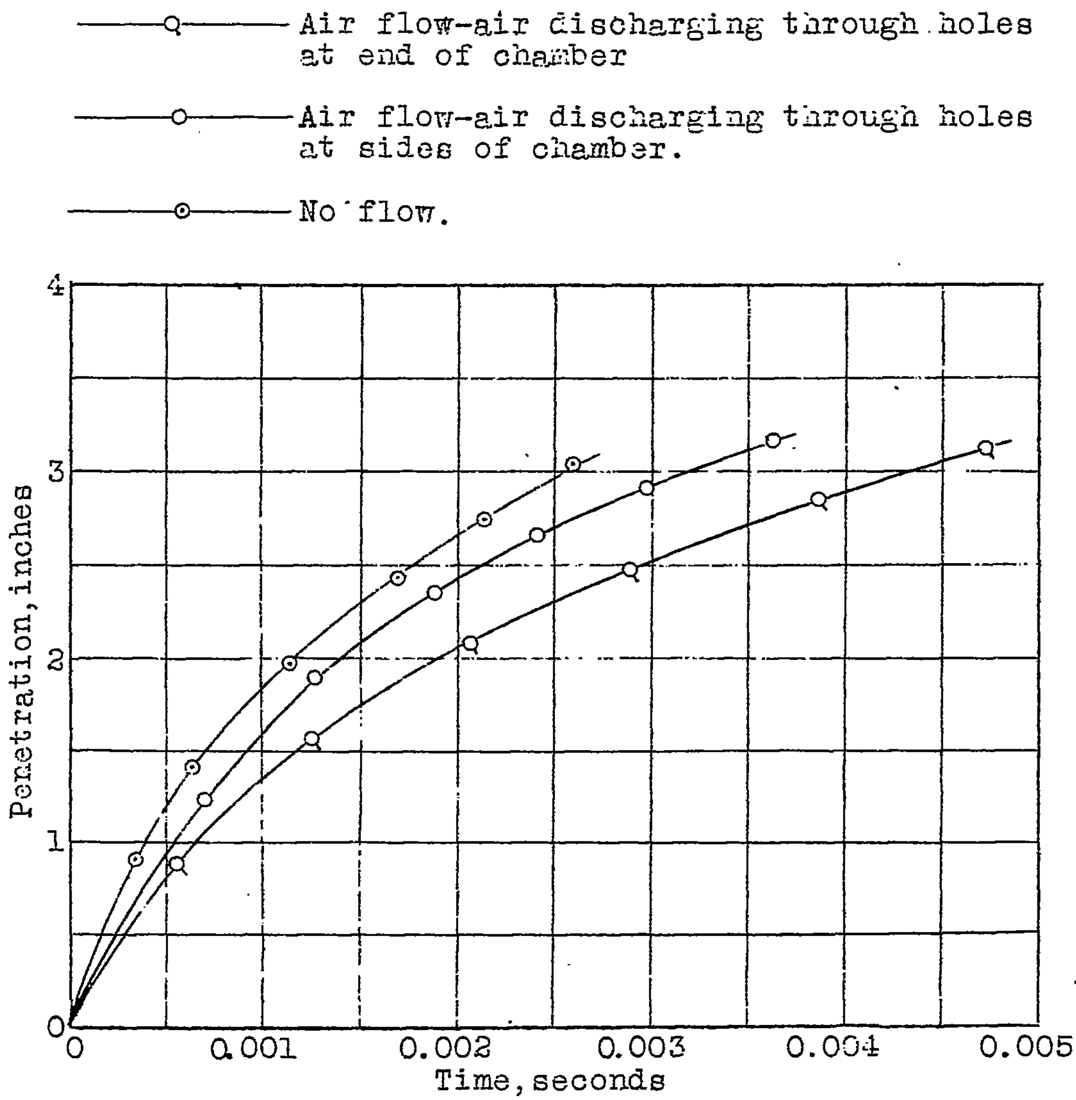


Fig.14 Effect of air flow on spray penetration.
Orifice diameter, 0.006 in.
Injection pressure, 6000 lb./sq. in.
Chamber pressure, 200 lb./sq. in.

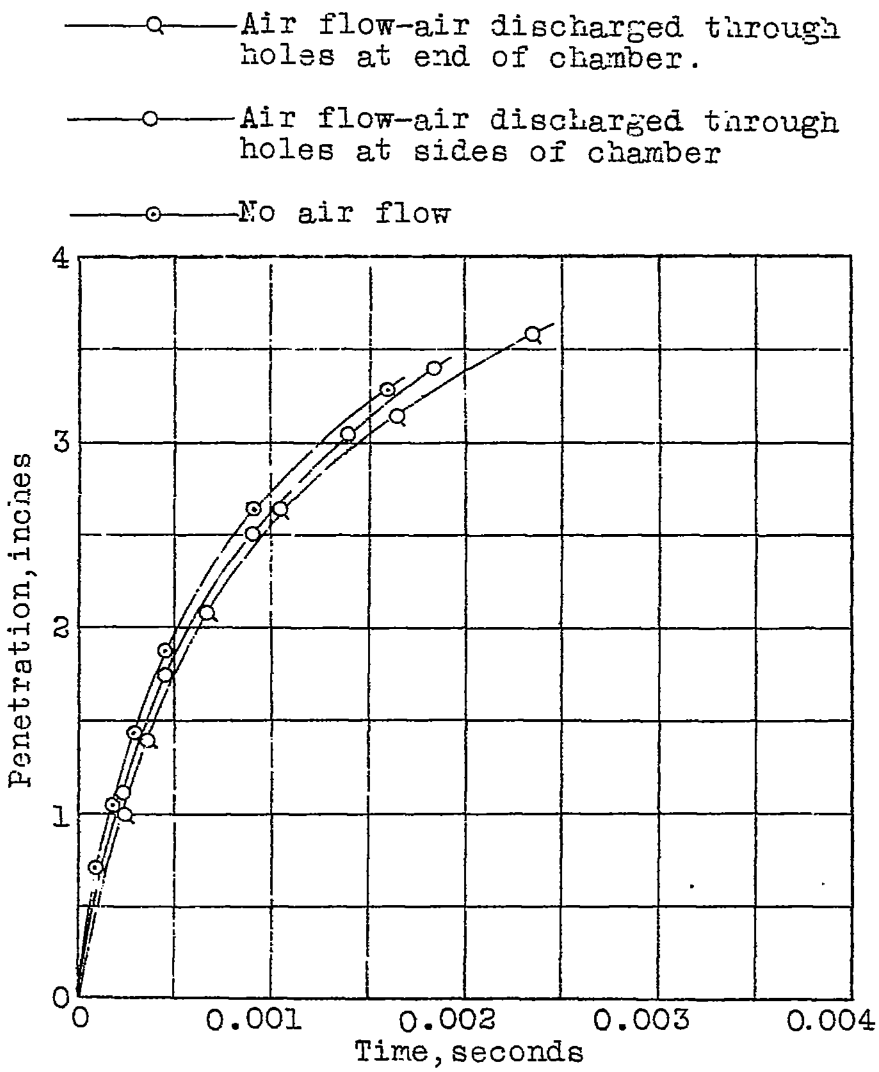


Fig.15 Effect of air flow on spray penetration.

Orifice diameter, 0.012 in.

Injection pressure, 6000 lb./sq. in.

Chamber pressure, 200 lb./sq.in.

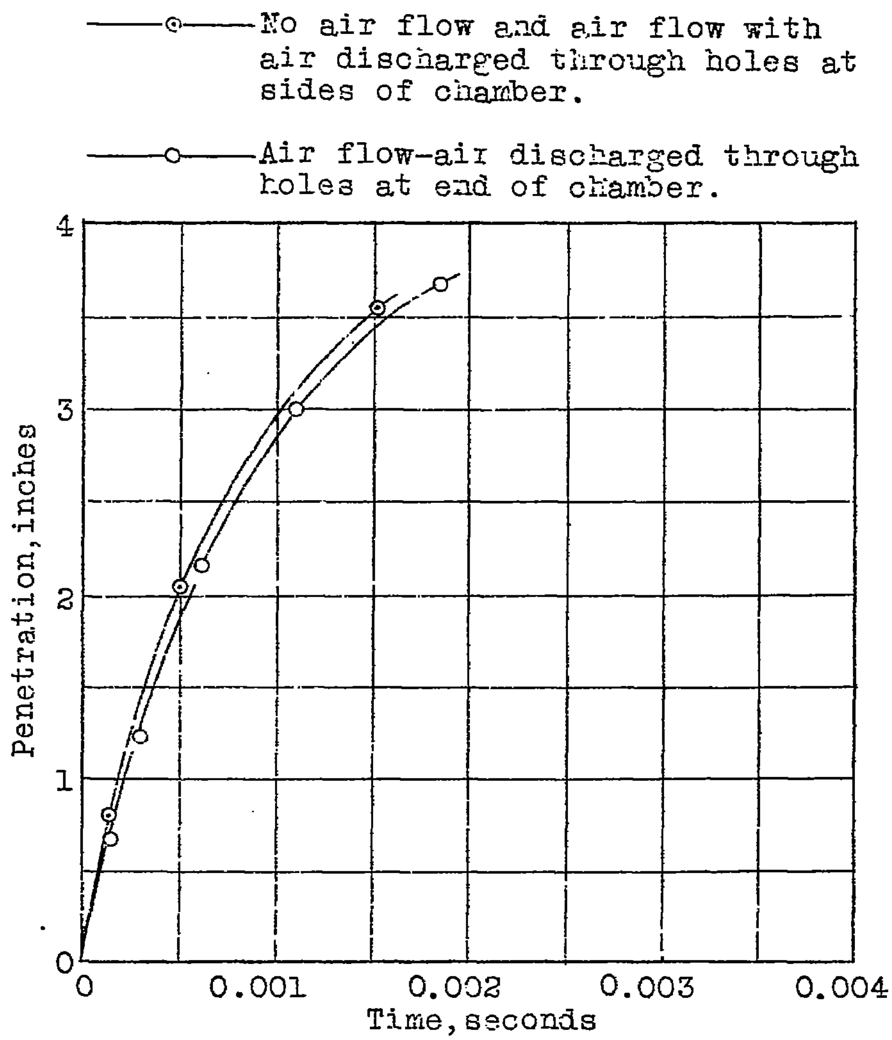


Fig.16 Effect of air flow on spray penetration.

Orifice diameter, 0.022 in.

Injection pressure, 6000 lb./sq. in.

Chamber pressure 200 lb./sq. in.